

CLAIMS

What is claimed is:

1. In a metrology system including a part-positioning means having a spindle axis and a wavefront-measuring gauge, a part-on-mount method for determining the position of a test part with respect to the spindle axis, and of the spindle axis with respect to the wavefront-measuring gauge, the method comprising the steps of:

a) mounting said test part onto said spindle axis such that a surface of said test part is exposed to said gauge;

b) obtaining measurements of said test part surface with said gauge at a plurality of rotary positions of said spindle;

c) extracting tilt components from said surface measurements at each of said rotary positions;

d) fitting a circle to said tilt components and said rotary positions; and

e) determining the center and radius coordinates of said circle to provide gauge-to-spindle and spindle-to-part misalignments, respectively.

2. A method in accordance with Claim 1 wherein said test part surface is selected from the group consisting of aspherical, spherical, and planar.

3. A method in accordance with Claim 2 wherein said fitting step includes a least-squares approximation.

4. A method in accordance with Claim 2 wherein said fitting step includes a visual inspection.

5. A method in accordance with Claim 1 including the prior step of measuring wedge/decentration of said spherical test part with some other method, and the additional step of subtracting the value obtained from said spindle-to-part misalignment value to uniquely determining both wedge and decentration of said test part.

6. A method in accordance with Claim 1, where the part-to-spindle interface includes one or more rotatable elements, each with its own contribution to the part-to-spindle misalignment, the method comprising the steps of:

a) performing the steps of Claim 1 to acquire a measurement of part-to-spindle misalignment at particular orientations of all rotatable components;

b) rotating at least one of said rotatable elements by a known amount;

c) performing the steps of Claim 1 to measure the part-to-spindle misalignment at these new orientations of the rotatable elements;

d) repeating steps b) and c) at least once for every extra rotatable component; and

e) performing mathematical analysis on all the part-to-spindle misalignment values to extract the misalignment contribution of each individual rotatable element.

7. A method in accordance with Claim 1 comprising the additional step of subtracting misalignment contributions from particular components in said part positioning means, in order to isolate the misalignment contribution from other components in said part-positioning means.

8. A method in accordance with Claim 1 for aligning said test surface to said spindle axis wherein the position of said part is adjusted with respect to said spindle axis to minimize the spindle-to-part misalignment value.

9. In a metrology system including a part-positioning means having a spindle axis and a wavefront-measuring gauge, a part-on-mount method for determining the position of a test part with respect to the spindle axis, assuming a particular gauge-to-spindle misalignment values, the method comprising the steps of:

- a) mounting said test part onto said spindle axis such that a surface of said test part is exposed to said gauge;
 - b) obtaining a measurement of said test part surface with said gauge at a rotary position of said spindle;
 - c) extracting tilt components from said surface measurement;
- and
- d) subtracting said assumed gauge-to-spindle misalignment values from said tilt components to provide an estimate of the spindle-to-part misalignments

10. A method for employing an embedded gauge and test surface to determine geometrical constants of a mechanical

positioning system including X, Y, and Z translational axes and A, B, and C rotational axes, wherein such constants may include lateral scale of the translational axes, spatial separations between the rotary axes, and axial position of a gauge focus with respect to a machine stage, the method comprising the steps of:

- a) providing said embedded gauge with a focusing element;
- b) mounting a test part having a test surface on said machine stage;
- c) setting the positions of said rotary axes to zero;
- d) moving said stage along at least one of said X and Y axes such that said A axis passes through the focus of said gauge;
- e) adjusting said translational axes such that said test surface is confocal with said embedded gauge;
- f) moving a one of said rotary axes to a new value;
- g) repositioning said test part at said confocal position by adjusting said translational axes;
- h) recording the positions of axes that achieve said confocal condition;
- i) repeating steps f) and g) for several different positions of said rotary axes; and
- j) performing a numerical fit to an analytical model of said machine geometry.

11. A method for aligning a wavefront-measuring gauge to a mechanical positioning system having a spindle axis, comprising the steps of:

- a) mounting said gauge, with focusing element removed, onto said mechanical positioning system;

b) adjusting mechanical axes of said mechanical positioning system to a desired work origin position;

c) placing a test part having at least one flat surface on said spindle;

d) using said gauge to measure angular misalignment between said spindle (A) axis and said gauge; and

e) re-orienting said gauge mainframe with respect to said mechanical positioning system, based on said angular misalignment measurement, to align said mainframe with said spindle axis.

12. A method in accordance with Claim 11 wherein step d) includes a part-on-mount procedure.

13. A method for calibrating and aligning a metrology system including a multi-axis mechanical positioning system and an embedded wavefront-measuring gauge to determine accurately the spatial relationships among the translational and rotational axes of the system, the method comprising the steps of:

a) coarsely aligning said mechanical positioning system rotary axes A, B, and C with said respective translational axes Z, Y, and X, and setting nominal zero points for said rotational axes;

b) aligning the mainframe of said embedded gauge to said mechanical positioning system;

c) aligning said embedded gauge onto said A rotational (spindle) axis;

d) determining spatial offsets between said rotational axes when so aligned; and

e) precisely aligning said machine rotational axes with said respective translational axes to set precise zero points for said rotational axes.

14. A method in accordance with Claim 13 wherein step b) includes the following steps:

- a) selecting a focusing element;
- b) mounting said focusing element onto said embedded gauge mainframe;
- c) aligning said focusing element to the optical axis of said gauge mainframe;
- d) installing a test part having at least one curved surface on a spindle axis of said positioning system;
- e) determining any misalignment between said spindle and said gauge optical axis by using said gauge; and
- f) moving said test part along one or more translational axes of said mechanical positioning system to eliminate said misalignment.

15. A method in accordance with Claim 14 wherein said focusing element is a transmission sphere and said embedded gauge is a Fizeau interferometer.

16. A method in accordance with Claim 14 wherein said determining step includes a part-on-mount procedure.

17. A method in accordance with Claim 13 wherein said embedded gauge generates a nominally collimated wavefront, and wherein step b) includes the following steps:

- a) mounting an optical flat in said collimated wavefront;
- b) installing a test part having at least one flat surface on a spindle axis of said positioning system;
- c) determining any misalignment between said spindle axis and the direction of said wavefront collimation by using said gauge; and
- d) moving at least one rotary axis of said mechanical positioning system to eliminate said misalignment.

18. A method in accordance with Claim 17 wherein said embedded gauge is a Fizeau interferometer.

19. A method in accordance with Claim 17 wherein said determining step includes a part-on-mount procedure.

20. In a metrology system including a multi-axis positioning machine and an embedded wavefront-measuring gauge in collimated mode, a method for determining the image position of a machine spindle axis in the gauge coordinate system, comprising the steps of:

- a) installing a test part having at least one flat surface on a spindle axis of said positioning machine exposed to said gauge wavefront, the aperture dimensions being fully contained in said gauge wavefront;
- b) measuring said part surface at a plurality of rotary positions of said spindle axis;
- c) extracting x-y coordinates in the gauge coordinate system from said measurements at each spindle position;
- d) fitting a circle to said x-y positions; and

e) determining the center and radius coordinates of said circle to provide both the position of the spindle image in the embedded gauge coordinate system and the part-to-spindle decentration misalignment, respectively.

21. In a metrology system including a wavefront-measuring gauge and part-positioning means having at least one rotational axis and at least one translational axis, a method for aligning said one rotational axis and said one translational axis comprising the steps of:

- a) mounting a test part on said rotational axis; and
- b) obtaining gauge measurements of the surface of said test part at a plurality of positions of said rotational axis.

22. A method in accordance with Claim 21 comprising the further step of obtaining gauge measurements of the surface of said test part at a plurality of positions along said translational axis.

23. A method in accordance with Claim 21 wherein said part-positioning means includes a second rotational axis, the method including, for more precise measurement of misalignment between the first rotational axis and the first translational axis, the further steps of:

- a) performing repeatedly the steps of Claim 21 at a plurality of different positions of said first translational axis using at least one spherical part mounted confocally at said plurality of first translational axis positions to generate a plurality of terms representing misalignment between said

gauge and said first rotational axis in a plane perpendicular to the second rotational axis;

b) fitting a line to said plurality of gauge misalignment terms plotted versus position along said first translational axis; and

c) calculating a misalignment angle of said rotational axis from said first translational axis in said plane, equal to the arctangent of the slope of said line fit.

24. A method in accordance with Claim 23 wherein step a) is performed using a plurality of spherical test parts having differing radii.

25. A method in accordance with Claim 23 wherein step a) is performed using a single spherical test part provided with a plurality of mounts having differing thicknesses.

26. A method in accordance with Claim 23 including the further step of adjusting the origin of said second rotary axis by said misalignment angle to reduce said misalignment.

27. A method in accordance with Claim 26 wherein said misalignment measurement and adjustment steps are performed iteratively to minimize said misalignment.

28. In a metrology system in accordance with Claim 21 wherein said part-positioning means include three translational axes, defined as X, Y, and Z, and three rotational axes, defined as A, B, and C, a method for precise measurement of the angle of

misalignment between the A rotational axis and Z translational axis, comprising the steps of:

a) performing repeatedly the steps of Claim 21 on a plurality of different positions of said Z axis using at least one spherical part mounted confocally at said plurality of Z axis positions to generate a plurality of X and Y direction misalignment terms representing misalignment between said gauge and said A axis;

b) fitting a line to said plurality of X and Y lateral gauge misalignment terms plotted against Z position; and

c) calculating said A-Z misalignment angles in said X and Y directions in both said X and Y directions, equal to the arctangent of the slope of said line fit in each of said X and Y directions, respectively.

29. A method in accordance with Claim 28 wherein said performing step includes the following part-on-mount steps to obtain said X and Y misalignment terms:

a) mounting said test part onto said spindle axis such that a surface of said test part is exposed to said gauge;

b) obtaining measurements of said test part surface with said gauge at a plurality of rotary positions of said spindle;

c) extracting tilt components from said surface measurements at each of said rotary positions;

d) fitting a circle to said tilt components and said rotary positions; and

e) determining the center and radius coordinates of said circle to provide gauge-to-spindle and spindle-to-part misalignments, respectively.

30. A method in accordance with Claim 28 including the further step of adjusting origins of said B and/or C rotary axes by said calculated misalignment angle to minimize said A-Z misalignment.

31. A method in accordance with Claim 30 wherein said misalignment measurement and adjustment steps are performed iteratively to improve and/or validate said minimizing of said A-Z misalignment.